

Unity of elementary particles and forces for the third family

Shreyashi Chakdar,^{1,*} Tianjun Li,^{2,3,†} S. Nandi,^{1,‡} and Santosh Kumar Rai^{1,§}

¹*Department of Physics and Oklahoma Center for High Energy Physics,
Oklahoma State University, Stillwater, OK 74078-3072, USA*

²*State Key Laboratory of Theoretical Physics and Kavli Institute for Theoretical Physics China (KITPC),
Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, P. R. China*

³*George P. and Cynthia W. Mitchell Institute for Fundamental Physics and Astronomy,
Texas A&M University, College Station, TX 77843, USA*

We propose a non-supersymmetric $SU(5)$ model in which only the third family of fermions are unified. The model remedies the non-unification of the three Standard Model couplings in non-supersymmetric $SU(5)$. It also provides a mechanism for baryon number violation which is needed for the baryon asymmetry of the Universe and is not present in the Standard Model. Current experimental constraints on the leptoquark gauge bosons, mediating such baryon and lepton violating interactions in our model, allow their masses to be at the TeV scale. These can be searched for as a $(b\tau)$ or (tt) resonance at the Large Hadron Collider as predicted in our model.

Introduction: In the highly successful Standard Model (SM) of elementary particle interactions, the baryon and lepton numbers happen to be accidental global symmetries of the renormalizable interactions, and are conserved. However, there is no fundamental reason why these symmetries should be exact in nature. In fact, in the SM, the lepton number is violated by the SM gauge invariant dimension-five operators [1], while baryon number is violated by dimension-six operators [1, 2]. The dimension-five operators can generate tiny neutrino masses [1], while the dimension-six operators can cause proton decay [1, 2]. However, if the ultra violet mass scale that suppresses these operators is the Planck scale, the generated neutrino masses are much smaller than the observed neutrino masses. Also, with the Planck scale suppression, the proton decay rate is too small to be observed in any future detector. The stability of proton was first questioned by Pati and Salam [3], and they proposed the $SU(4) \times SU(2)_L \times SU(2)_R$ model (where the lepton number is the fourth color) [4] in which there are leptoquark gauge bosons violating both baryon and lepton numbers. These leptoquark gauge boson exchanges do not cause proton decay, but do cause $K_L \rightarrow \mu e$ transition [5]. The current limit on this branching ratio, $B(K_L \rightarrow \mu e) = 4.7 \times 10^{-12}$ [6] gives the mass limit on these leptoquark gauge bosons to be greater than 2300 TeV. So this type of leptoquark gauge bosons is beyond the reach of the LHC. The minimal Grand Unified Theory (GUT) unifying the three SM gauge interactions was proposed by Georgi and Glashow with the $SU(5)$ gauge symmetry [7]. However, the three SM gauge couplings do not unify in non-supersymmetric $SU(5)$. This model also has leptoquark gauge bosons X_μ and Y_μ leading to proton decay. Again the stability of the proton requires $M_{X_\mu}, M_{Y_\mu} > 10^{16}$ GeV. Same is true for the $SO(10)$ GUT [8].

While the proton stability and $K_L \rightarrow \mu e$ process put severe limit on the masses of the leptoquark gauge bosons

involving the first and second families of the SM fermions, no such severe limit exists for the baryon and lepton number violating interactions involving the third family. For the first generation leptoquark searches at the 7 TeV LHC, CMS Collaboration with 36 pb^{-1} data has looked for the pair production of leptoquarks [9], and each decaying to lq (with $l = e$ or ν and q being a light jet) with a branching ratio, $\beta = 1$ and 0.5 . They have set a limit, $M_{LQ} > 384$ GeV for the $eeqq$ final state, and $M_{LQ} > 339$ GeV for the $evqq$ final state. The corresponding 95% C.L. limits on second generation leptoquarks from CMS with 2 fb^{-1} of data is $M_{LQ} > 632(523)$ GeV for $\beta = 1.0(0.5)$ [10] while ATLAS with 1.03 fb^{-1} of data set the limits as $M_{LQ} > 685(594)$ GeV for $\beta = 1.0(0.5)$ [11]. For their third generation leptoquark search, with 1.8 fb^{-1} of data in the final state $bb\nu\nu$, their limit is $M_{LQ} > 350$ GeV at 95% C.L. [12]. The bound from the Tevatron is weaker [13]. Thus for a leptoquark decaying to the third generation only, the limit on its mass is very low. In particular, a leptoquark decaying to $b\tau$ or tt has not been looked at yet.

In this work, we propose a top $SU(5)$ model which remedies the non-unification of the three SM couplings in the non-supersymmetric $SU(5)$ model. As our non-supersymmetric model is constructed using the $SU(5) \times SU(3)' \times SU(2)' \times U(1)'$, the SM couplings are combinations of the corresponding couplings of (g_5, g_3') , (g_5, g_2') and (g_5, g_1') ; and thus no unification of the SM couplings is needed. It also gives a mechanism for baryon number violation which is needed for the baryon asymmetry of the Universe and is not present in the SM. The baryon and lepton violating gauge interactions involve only the third generation of the SM fermions. The leptoquark gauge bosons mediating these interactions are $(X_\mu, Y_\mu) = (3, 2, 5/6)$ where the numbers inside the parenthesis represent the quantum numbers with respect to the SM $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry. The X_μ decays to tt and $\bar{b}\tau^+$ while Y_μ decays to tb , $\bar{t}\tau^+$,

and $\bar{b}\nu$, which violate the baryon and lepton numbers. If we choose a basis such that the up-type quark mass matrix is diagonal and the quark CKM mixings arise solely from the down-type quark sector, there will be no interactions of the Xuu or Yud type, thus preventing the proton decay. Since the leptoquark gauge bosons are color triplets, they can be pair produced ($X\bar{X}$, $Y\bar{Y}$) if their masses are at the TeV scale. From their decays to $X \rightarrow \bar{b}\tau^+$ (or $\bar{X} \rightarrow b\tau^-$), one can reconstruct the resonance by taking suitable combinations of b and τ in the final state, $b\bar{b}\tau^+\tau^-$. The same might be possible in the $t\bar{t}$ channel if $t's$ can be reconstructed from their decay products. Below we present our model realizing this scenario.

Top $SU(5)$ Model and the Formalism: Our model is an interesting unification of topcolor [14, 15], topflavor [16], and top hypercharge [17] models. We call it top $SU(5)$ model. Our gauge symmetry is $SU(5) \times SM'$ where $SM' = SU(3)'_C \times SU(2)'_L \times U(1)'_Y$. The first two families of the SM fermions are charged under SM' and singlet under the $SU(5)$, while the third family is charged under $SU(5)$ and singlet under SM' . We denote the gauge fields for $SU(5)$ and $SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ as \hat{A}_μ and \tilde{A}_μ , respectively, and the gauge couplings as g_5 , g'_3 , g'_2 and g'_Y , respectively. The Lie algebra indices for the generators of $SU(3)$, $SU(2)$ and $U(1)$ are denoted by $a3$, $a2$ and $a1$, respectively, and the Lie algebra indices for the generators of $SU(5)/(SU(3) \times SU(2) \times U(1))$ are denoted by \hat{a} . After the $SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ gauge symmetry is broken down to the SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, we denote the massless gauge fields for the SM gauge symmetry as A_μ^{ai} , and the massive gauge fields as B_μ^{ai} , $\hat{X}_\mu^{\hat{a}}$ and $\hat{Y}_\mu^{\hat{a}}$. The X_μ and Y_μ are the leptoquark gauge bosons. The gauge couplings for the SM gauge symmetry $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ are g_3 , g_2 and g_Y , respectively.

To break the $SU(5) \times SM'$ gauge symmetry down to the SM gauge symmetry, we introduce two bifundamental Higgs fields U_T and U_D [18]. The fermion and Higgs field content of our models are shown in the first six rows of Table I. The first two family quark doublets, right-

handed up-type quarks, right-handed down-type quarks, lepton doublets, right-handed neutrinos, right-handed charged leptons, and the corresponding Higgs field (belonging to SM') are denoted as Q_i , U_i^c , D_i^c , L_i , N_i^c , E_i^c , and H respectively. The third family SM fermions are F_3 , \bar{f}_3 , and N_3^c . To give mass to the third family of the SM fermions, we introduce an $SU(5)$ anti-fundamental Higgs field $\Phi \equiv (H'_T, H')$. This would be the minimal top $SU(5)$ model in terms of field content. However, we then need to introduce the higher-dimensional (non-renormalizable) operators in the Higgs potential for the down-type quark Yukawa coupling terms between the first two families and third family. Instead, we construct a renormalizable top $SU(5)$ model by introducing additional fields: the scalar field XU , and the vector-like fermions (Xf , $\bar{X}\bar{f}$), (XD , $\bar{X}\bar{D}$), and (XL , $\bar{X}\bar{L}$). To give the triplet Higgs H'_T mass around 1 TeV, we also need to introduce a scalar field XT . Otherwise, H'_T will have mass around a few hundred of GeV. The SM quantum numbers for these extra particles are given in Table I as well. We shall present these two models in detail in a forthcoming paper [19].

Particles	Quantum Numbers	Particles	Quantum Numbers
Q_i	(1; 3, 2, 1/6)	L_i	(1; 1, 2, -1/2)
U_i^c	(1; 3, 1, -2/3)	N_k^c	(1; 1, 1, 0)
D_i^c	(1; 3, 1, 1/3)	E_i^c	(1; 1, 1, 1)
F_3	(10; 1, 1, 0)	\bar{f}_3	(5; 1, 1, 0)
H	(1; 1, 2, -1/2)	Φ	(5; 1, 1, 0)
U_T	(5; 3, 1, 1/3)	U_D	(5; 1, 2, -1/2)
XT	(1; 3, 1, 1/3)	XU	(10; 1, 1, -1)
Xf	(5; 1, 1, 0)	$\bar{X}\bar{f}$	(5; 1, 1, 0)
XD	(1; 3, 1, -1/3)	$\bar{X}\bar{D}$	(1; 3, 1, 1/3)
XL	(1; 1, 2, -1/2)	$\bar{X}\bar{L}$	(1; 1, 2, 1/2)

TABLE I: The complete particle content and the particle quantum numbers under $SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ gauge symmetry in the top $SU(5)$ model. Here, $i = 1, 2$ and $k = 1, 2, 3$.

The Higgs potential breaking the $SU(5) \times SM'$ down to the SM gauge symmetry is given by

$$V = -m_T^2|U_T^2| - m_D^2|U_D^2| + \lambda_T|U_T^2|^2 + \lambda_D|U_D^2|^2 + \lambda_{TD}|U_T^2||U_D^2| + \left[A_T\Phi U_T XT^\dagger + A_D\Phi U_D H^\dagger + \frac{y_{TD}}{M_*}U_T^3 U_D^2 + \text{H.C.} \right], \quad (1)$$

The non-renormalizable y_{TD} term is needed to give mass to the remaining Goldstone boson in our model, and is generated from the renormalizable interactions involving the fields, U_T , U_D and XU , with $M_* \simeq M_{XU} \simeq 1000$ TeV [19].

We choose the following vacuum expectation values

(VEVs) for the fields U_T and U_D

$$\langle U_T \rangle = v_T \begin{pmatrix} I_{3 \times 3} \\ 0_{2 \times 3} \end{pmatrix}, \quad \langle U_D \rangle = v_D \begin{pmatrix} 0_{3 \times 2} \\ I_{2 \times 2} \end{pmatrix}, \quad (2)$$

where $I_{i \times i}$ is the $i \times i$ identity matrix, and $0_{i \times j}$ is the $i \times j$ matrix where all the entries are zero. We assume

that v_D and v_T are in the TeV range so that the massive gauge bosons have TeV scale masses.

From the kinetic terms for the fields U_T and U_D , we obtain the mass terms for the gauge fields

$$\begin{aligned} \sum_{i=T,D} \langle (D_\mu U_i)^\dagger D^\mu U_i \rangle &= \frac{1}{2} v_T^2 \left(g_5 \hat{A}_\mu^{a3} - g'_3 \tilde{A}_\mu^{a3} \right)^2 \\ &+ \frac{1}{2} v_D^2 \left(g_5 \hat{A}_\mu^{a2} - g'_2 \tilde{A}_\mu^{a2} \right)^2 + \left(\frac{v_T^2}{3} + \frac{v_D^2}{2} \right) \left(g_5^Y \hat{A}_\mu^{a1} - g'_Y \tilde{A}_\mu^{a1} \right)^2 \\ &+ \frac{1}{2} g_5^2 (v_T^2 + v_D^2) (X_\mu \bar{X}_\mu + Y_\mu \bar{Y}_\mu), \end{aligned} \quad (3)$$

where $g_5^Y \equiv \sqrt{3}g_5/\sqrt{5}$, and we define the complex fields (X_μ, Y_μ) and $(\bar{X}_\mu, \bar{Y}_\mu)$ with quantum numbers $(3, 2, 5/6)$ and $(\bar{3}, 2, -5/6)$, respectively from the gauge fields \hat{A}_μ^a , similar to the usual $SU(5)$ model [7].

The $SU(5) \times SU(3)_C \times SU(2)_L' \times U(1)_Y'$ gauge symmetry is broken down to the diagonal SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, and the theory is unitary and renormalizable. The SM gauge couplings g_j ($j = 3, 2$) and g_Y are given by

$$\frac{1}{g_j^2} = \frac{1}{g_5^2} + \frac{1}{(g_j')^2}, \quad \frac{1}{g_Y^2} = \frac{1}{(g_5^Y)^2} + \frac{1}{(g_Y')^2}. \quad (4)$$

The renormalizable SM fermion Yukawa couplings are

$$\begin{aligned} -\mathcal{L} &= y_{ij}^u U_i^c Q_j \tilde{H} + y_{kj}^\nu N_k^c L_j \tilde{H} + y_{ij}^d D_i^c Q_j H \\ &+ y_{ij}^e E_i^c L_j H + y_{33}^u F_3 F_3 \Phi^\dagger + y_{33}^{d,e} F_3 \bar{F}_3 \Phi \\ &+ y_{k3}^\nu N_k^c \bar{F}_3 \Phi^\dagger + m_{kl}^N N_k^c N_l^c + \text{H.C.}, \end{aligned} \quad (5)$$

where $i/j = 1, 2, k/l = 1, 2, 3$, and $\tilde{H} = i\sigma_2 H^*$ with σ_2 being the second Pauli matrix. Because the three right-handed neutrinos can mix among themselves via the Majorana masses, we can generate the observed neutrino masses and mixings via TeV scale seesaw. In addition, the Yukawa terms between the triplet Higgs field H'_T in Φ and the third family of the SM fermions are $y_{33}^{d,e} t^c b^c H'_T$, $y_{33}^{d,e} Q_3 L_3 H'_T$, and $y_{33}^{d,e} \tau^c H'_T$. So, we have $(B + L)$ violating interactions as well.

It is worth pointing out here that we have chosen a basis in which the up-type quark Yukawa interactions and hence the up-quark mass matrix is diagonal. Therefore the quark CKM mixings need to be generated from the down-type quark sector. But the Yukawa couplings of Eq. (5) have no mixing of the first and second families with the third family. So to generate the quark CKM mixing, we consider the dimension-five operators given by

$$\begin{aligned} -\mathcal{L} &= \frac{1}{M_*} \left(y_{i3}^d D_i^c F_3 \Phi U_T^\dagger + y_{i3}^e E_i^c \bar{F}_3 H U_D \right. \\ &\left. + y_{3i}^d \bar{F}_3 Q_i H U_T + y_{3i}^e F_3 L_i \Phi U_D^\dagger \right) + \text{H.C.} \end{aligned} \quad (6)$$

The correct CKM mixings can be generated with $M_* \simeq 1000$ TeV. The dimension-five terms in Eq. (6) can be generated at the renormalizable level by using the vector-like fermions $(Xf, \bar{X}\bar{f})$, $(XD, \bar{X}\bar{D})$, and $(XL, \bar{X}\bar{L})$ with masses around 1000 TeV [19]. Note that the

dimension-five operators are generated using the vector like fermions only for the down sector. No such terms are generated for the up sector at the tree level or radiatively.

We note that there is no proton decay in our model, because no up-type quark mixings can be generated after we integrate out the vector-like particles. This can be seen as follows. The $SU(3)_C' \times SU(2)_L' \times U(1)_Y'$ gauge symmetry can be formally embedded into a global $SU(5)'$ symmetry. Under $SU(5) \times SU(5)'$, the bi-fundamental fields U_T and U_D form $(\mathbf{5}, \bar{\mathbf{5}})$ representation, the vector-like particles Xf and $\bar{X}\bar{f}$ respectively form $(\mathbf{5}, \mathbf{1})$ and $(\bar{\mathbf{5}}, \mathbf{1})$ representations, and the vector-like particles $(XD, \bar{X}\bar{L})$ and $(\bar{X}\bar{D}, XL)$ respectively form $(\mathbf{1}, \mathbf{5})$ and $(\mathbf{1}, \bar{\mathbf{5}})$ representations. Because all these fields are in the fundamental and/or anti-fundamental representations of $SU(5)$ and/or $SU(5)'$, we cannot create the Yukawa interactions $10_f 10_f' 5_H$ or $10_f 10_f' 5_{H'}$ for the up-type quarks after we integrate out the vector-like particles. Thus, there is no proton decay problem. We also note that there is no Landau pole in our model. The ultraviolet cutoff scale could be the Planck scale, since the $SU(5)$ is asymptotically free.

Phenomenology and LHC Signals: Leptoquark production at LHC will have large cross sections [20]. The leptoquark gauge bosons, X_μ and Y_μ can be pair produced at the LHC, *viz.* $pp \rightarrow X\bar{X}$ and $pp \rightarrow Y\bar{Y}$. In our model, the decay modes of X_μ are to $\bar{b}\tau^+$ and $t\bar{t}$, with the former mode dominating at the low X_μ mass region. The modes of Y_μ are to $\bar{b}\nu$, $\bar{t}\tau^+$, and $t\bar{b}$.

We consider here, the signal at the 7 TeV and 8 TeV runs of LHC, coming from the $X\bar{X}$ production, with X_μ decaying to $\bar{b}\tau^+$, and \bar{X}_μ decaying to $b\tau^-$, as these will be relatively less difficult modes to reconstruct the mass of X_μ and \bar{X}_μ from the decays. The final state signal is $\bar{b}b\tau^+\tau^-$ with all four particles being detected in the flavor tagged mode, *albeit* with respective tagging efficiencies. Although the τ modes can be distinguished by their charge, the b and \bar{b} cannot be distinguished from each other. Thus to reconstruct the mass of the X_μ we need to pair the τ^\pm with both the b jets. The dominant SM background for our final state comes from $pp \rightarrow 2b2\tau, 4b, 2j2b, 2j2\tau, 4j, t\bar{t}$ where $j = u, d, s, c$. The light jet final states can be mistagged as τ or b jets and thus form a significant source for the background due to the large cross sections at LHC, as they are dominantly produced through strong interactions. We find that at leading-order and with a kinematic selection of $p_T > 15$ GeV, $|\eta| < 2.5$ and $\Delta R > 0.2$ for all four particles, the SM background at LHC with $\sqrt{s} = 7$ TeV is $\simeq 9.7$ pb while it is $\simeq 11.7$ pb at LHC with $\sqrt{s} = 8$ TeV estimated using **Madgraph 5** [21]. However the background is significantly suppressed to ~ 1.6 fb when we choose stronger cuts of $p_T > 80$ GeV and $\Delta R > 0.4$ for all particles. Also for similar cuts the SM background at LHC with $\sqrt{s} = 8$ TeV is estimated to be around

~ 2.5 fb. Note that we have used the following efficiencies for b and τ tagging, $\epsilon_b = \epsilon_\tau = 0.5$ while we assume a mistag rate for light jets to be tagged as b or τ as 1% and c jets tagged as b jets to be 10%. For analyzing the signal we choose two values for the mass of X_μ , *viz.* $M_X = 600(800)$ GeV which are pair produced at 7 and 8 TeV run of LHC with production cross sections of $\sim 275.5(559.5)$ fb and $\sim 23.5(55.7)$ fb respectively. The pair produced leptoquarks would then decay to give us the $b\bar{b}\tau^+\tau^-$ final state. To account for the detector resolutions for energy measurement of particles, we have used a Gaussian smearing of the jet and τ energies with an energy resolution given by $\Delta E/E = 0.8/\sqrt{E} \text{ (GeV)}$ and $\Delta E/E = 0.15/\sqrt{E} \text{ (GeV)}$ respectively when analyzing the signal events. The strong cuts on the final states do not affect the signal too much as the final state particles come from the decay of a heavy parent particle and therefore carry large transverse momenta. This gives us cross sections for the $2b2\tau$ final state as 7.5 fb for

$M_X = 600$ GeV and 0.62 fb for $M_X = 800$ GeV which were 8.4 fb and 0.67 fb for the two masses respectively, with the less stringent cuts at LHC with $\sqrt{s} = 7$ TeV. Similarly, one finds that for the current run of LHC with $\sqrt{s} = 8$ TeV, we get signal cross sections of 14.8 fb for $M_X = 600$ GeV and 1.5 fb for $M_X = 800$ GeV with the stronger kinematic cuts. The corresponding numbers with the less stringent cuts were 17 fb and 1.6 fb respectively. Note that we have included the tagging efficiencies and the corresponding branching fraction of the X_μ decaying to the $b\tau$ mode in evaluating the above quoted numbers for the signal cross section. A quick look at the signal and SM background cross sections shows that a resonance in the invariant mass distribution of the $b\tau$ final state for the signal for mass $M_X = 600$ GeV at LHC with $\sqrt{s} = 7$ TeV and for $M_X = 800$ GeV at LHC with $\sqrt{s} = 8$ TeV would clearly stand out against the very small SM background.

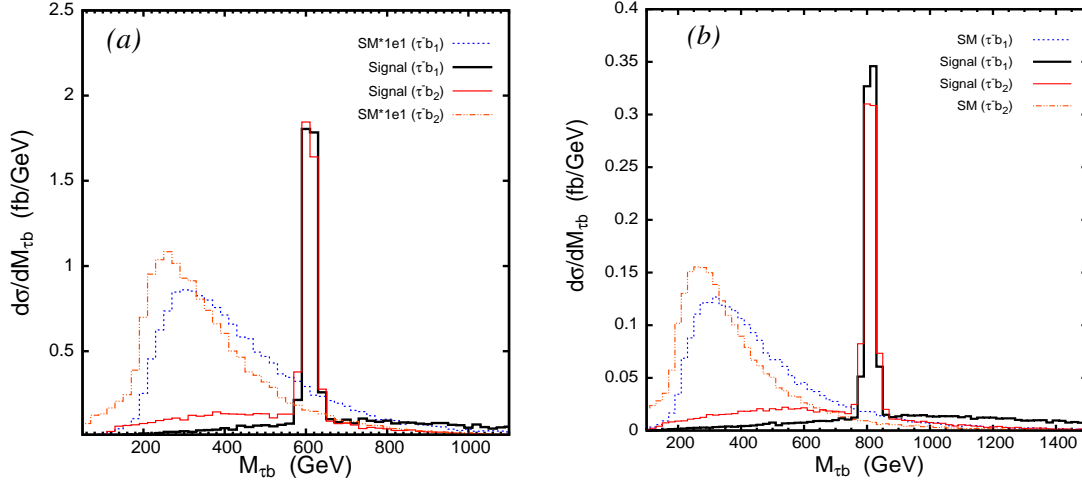


FIG. 1: The invariant mass distribution in τ^-b for the signal corresponding to (a) $M_X = 600$ GeV at LHC with $\sqrt{s} = 7$ TeV and (b) $M_X = 800$ GeV at LHC with $\sqrt{s} = 8$ TeV. Also included are the SM distributions where the background has been multiplied by a factor of 10 in (a).

To put this in perspective, in Fig.1, we plot the invariant mass distribution of the τ^- with either of the b jets which are ordered according to their p_T for the two choices of the X_μ mass. We clearly see the leptoquark (X_μ) peak around 600 GeV and 800 GeV in the signal while the SM events fall off rapidly at high values of the invariant mass. Note that as the b jets are ordered according to their p_T , so either can form the correct combination with the charged τ for the peak and thus both distributions lead to a peak in the invariant

mass. It is also worth noting that if such a p_T ordering is used then either b jet combined with either of the charged τ will give an invariant mass peak at the same mass. The SM background is quite suppressed compared to the signal for LHC with $\sqrt{s} = 7$ TeV and is shown after multiplying by a factor of 10 in Fig.1(a). As can be seen from Fig.1, the signals are clearly visible above the background. Therefore a dedicated search in invariant mass bins in the $b\tau$ channel will be very useful in searching for such a leptoquark signal, even with small

signal cross sections. To highlight this we also estimate that with the data available ($5 fb^{-1}$) at 7 TeV collisions at LHC, the leptoquark in our model will give 5 signal events for mass as high as 750 GeV. The reach would be further improved at the current run of LHC with center of mass energy of 8 TeV. We find that we get 5 signal events with data corresponding to an integrated luminosity of $5 fb^{-1}$ already collected at 8 TeV collisions, for leptoquark mass of 840 GeV while with an integrated luminosity of $15 fb^{-1}$ achievable in the near foreseeable future one can get 5 signal events for leptoquark mass as high as 940 GeV. Another promising final state is $ttb\tau^-$ arising from the decays $X \rightarrow tt$, and $\bar{X} \rightarrow \bar{b}\tau^-$, if the top quarks can be reconstructed. The pair production of the Y_μ leptoquark gauge bosons also lead to many interesting signals. Details of these and other multijet and multilepton final states with or without missing energy will be discussed in a forthcoming publication [19].

Summary and Conclusions: We have presented a top $SU(5)$ model which remedies the non-unification of the three SM couplings in the non-supersymmetric $SU(5)$ model. The model has baryon and lepton number violation which is needed to explain the baryon asymmetry of the Universe and is not present in the SM. Our model is renormalizable and satisfy all the existing experimental constraints, and do not cause proton decay. The gauge bosons, X_μ and Y_μ , which mediate baryon and lepton number violating interactions, involve only the third family of fermions, and can be pair produced at the LHC. X_μ can be reconstructed as a $\bar{b}\tau^+$ resonance in the four jet final state, as well as, possibly in the (tt) mode. We encourage our ATLAS and CMS colleagues to search for these leptoquark gauge bosons in the proposed final states.

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[†] Electronic address: tli@itp.ac.cn

[‡] Electronic address: s.nandi@okstate.edu

[§] Electronic address: santosh.raai@okstate.edu

- [1] S. Weinberg, Phys. Rev. Lett. **43**, 1566 (1979).
- [2] F. Wilczek and A. Zee, Phys. Rev. Lett. **43**, 1571 (1979).
- [3] J. C. Pati and A. Salam, Phys. Rev. Lett. **31**(1973)661.
- [4] J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 566 (1975).
- [5] G. Valencia and S. Willenbrock, Phys. Rev. D **50**, 6843 (1994) [hep-ph/9409201].
- [6] K. Nakamura et al. (Particle Data Group), J. Phys. G **37**, 075021 (2010) and 2011 partial update for the 2012 edition.
- [7] H. Georgi and S. L. Glashow, Phys. Rev. Lett. **32**, 438 (1974).
- [8] H. Georgi, *Particles and Fields*, 1974 (APS/DPF Williamsburg), ed. C. E. Carlson (AIP, New York, 1975) p.575; H. Fritzsch and P. Minkowski, Annals Phys. **93**, 193 (1975).
- [9] V. Khachatryan et. al [CMS Collaboration] Phys. Rev. Lett. **106**, 201802 (2011).
- [10] V. Khachatryan et. al [CMS Collaboration], Report No. CMS-EXO-11-028.
- [11] G. Aad et al. [ATLAS Collaboration], arXiv:1203.3172 [hep-ex].
- [12] V. Khachatryan et. al [CMS Collaboration], Report No. CMS-EXO-11-030.
- [13] V. M. Abazov et al. [D0 Collaboration], Phys. Lett. B **693**, 95 (2010); Phys. Rev. Lett. **99**, 061801 (2007).
- [14] C. T. Hill, Phys. Lett. B **266**, 419 (1991); Phys. Lett. B **345**, 483 (1995).
- [15] C. T. Hill and S. J. Parke, Phys. Rev. D **49**, 4454 (1994); D. A. Dicus, B. Dutta and S. Nandi, Phys. Rev. D **51**, 6085 (1995).
- [16] D. J. Muller and S. Nandi, Phys. Lett. B **383**, 345 (1996); E. Malkawi, T. Tait and C. P. Yuan, Phys. Lett. B **385**, 304 (1996). H. Georgi, E. E. Jenkins, and E. H. Simmons, Nucl.Phys. B331, 541 (1990).
- [17] C. -W. Chiang, J. Jiang, T. Li and Y. -R. Wang, JHEP **0712**, 001 (2007).
- [18] T. Li and S. Nandi, Phys. Lett. B **617**, 112 (2005).
- [19] S. Chakdar, T. Li, S. Nandi, and S. K. Rai, in preparation.
- [20] J. Blumlein, E. Boos and A. Kryukov, Z. Phys. C **76**, 137 (1997); A. Belyaev, C. Leroy, R. Mehdiyev and A. Pukhov, JHEP **0509**, 005 (2005).
- [21] J. Alwall, et.al., J. High Energy Phys. **06** (2011) 128.

* Electronic address: chakdar@okstate.edu